Impact of forging direction on the recrystallization behaviour of nickel base superalloy AD730 billet material at subsolvus temperatures

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Background and Motivation

AD730 Ni-based superalloy

Nickel superalloys are used to manufacture high temperature rotary engine parts such as high pressure disks in gas turbine engines. In this application high strength at high operating temperatures is required due to the levels of stress and heat the disk must withstand. Additionally, the higher the temperature of a gas turbine engine the more fuel efficient it is, which is desirable for commercial airplane companies.

High strength turbine disks can be made by powder metallurgy which is an expensive and undesirable production route. A manufacturing process referred to as the triple melt process has made the production of cast and wrought (C&W) nickel superalloys possible, optimizing the balance of cost and performance at high temperature.

AD730™ is a newly developed Ni-based superalloy for turbine disk applications, with reported superior service properties around 700 °C when compared to Inconel 718 and several other alloys. This alloy is a γ' strengthened alloy (≈ 40% γ' volume fraction) produced by cast and wrought processes.

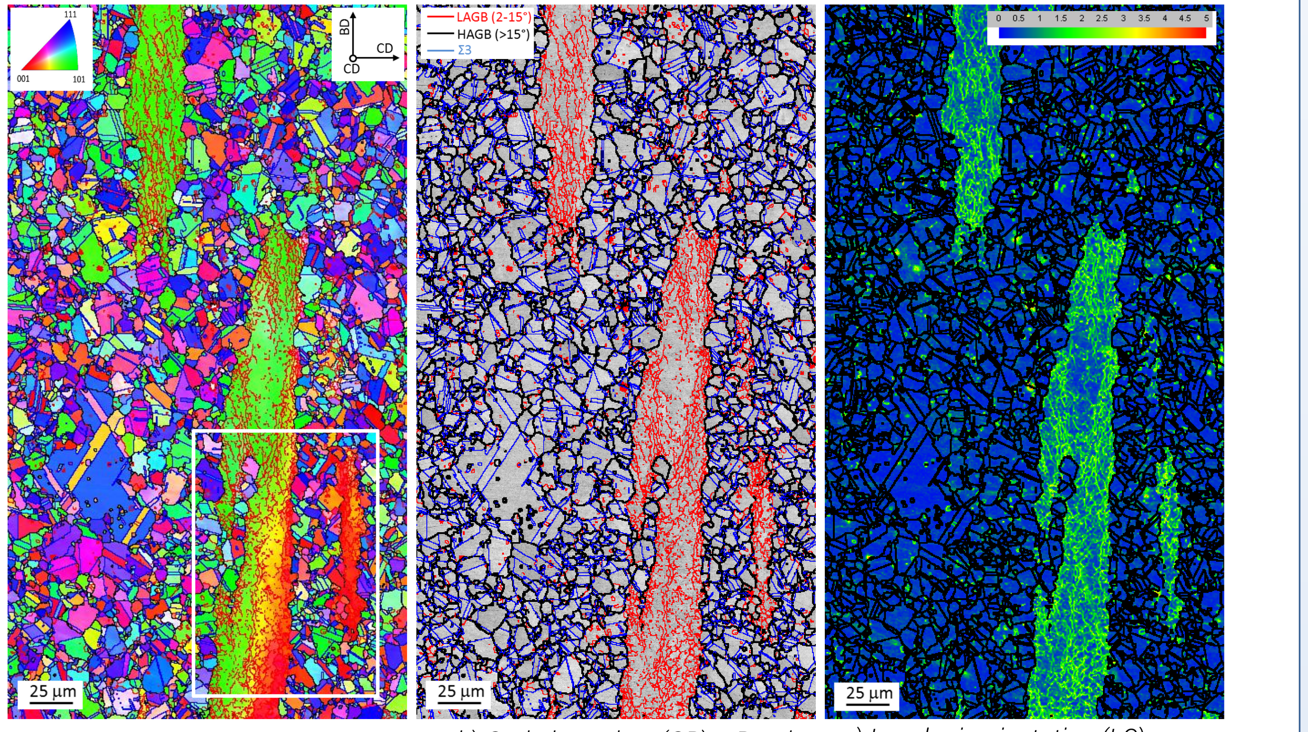
Cogging operations

Conventional ingot-to-billet conversion is an expensive and very complex operation (Figure 1). Because of the difficulties to achieve a uniform strain for recrystallization, large unrecrystallized grains are retained along this process (Figure 2). Heterogeneities of grain size have a negative impact on subsequent forming processes as well as ultrasonic inspectability of the destination part.

Figure 1: Example of cogging operations

Main purpose

The main aim of this work is to analyse the effect of both forging direction and level of deformation on the microstructural evolution of the nickel base superalloy AD730™ from a semi-finished product (billet) during hot forging at subsolvus temperatures (1070 °C).



a) Inverse Pole Figure (IPF) *b) Grain boundary (GB) + Band Contrast (BC) map* *c) Local misorientation (LC) map*

Figure 2: EBSD analysis of AD730 material from a ⌀203 mm billet

Methods

Material and forging trials

AD730 blocks from a ⌀203 mm billet were supplied by Aubert & Duval (Les Ancizes, France). Double truncated cones (DTCs) of ⌀120 × 90 mm were machined along both the billet (BD) and the cogging directions (CD), see Figure 3.

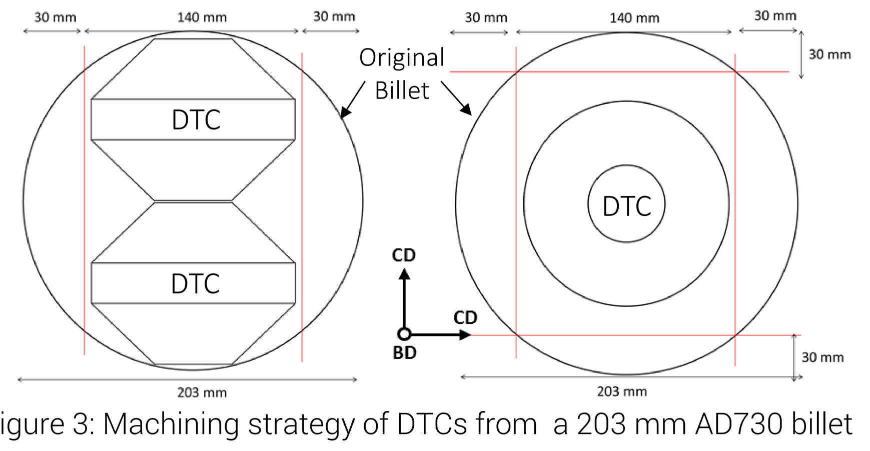


Figure 3: Machining strategy of DTCs from a 203 mm AD730 billet

Hot forging trials of DTCs were carried out in hydraulic press (AFRC, Glasgow) at subsolvus temperatures (1070 °C), at a constant strain rate (0.05 s^{-1}) and with die temperatures of 435 C. A 60% height reduction was introduced in one single blow. Prior to hot forging, the DTCs were preheated by isothermal holding during 1 hour at 1070 °C. After forging, the DTCs were cooled in air (Figure 4). No defects or cracks were found in the hot forged DTCs, see Figure 5.

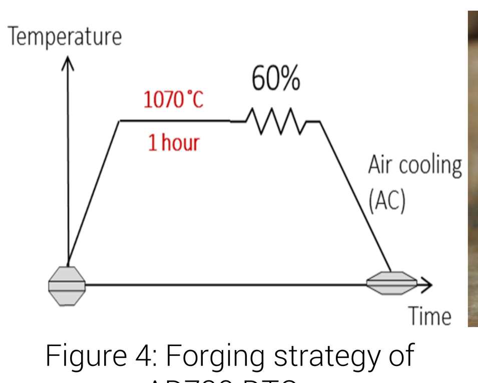


Figure 4: Forging strategy of AD730 DTCs

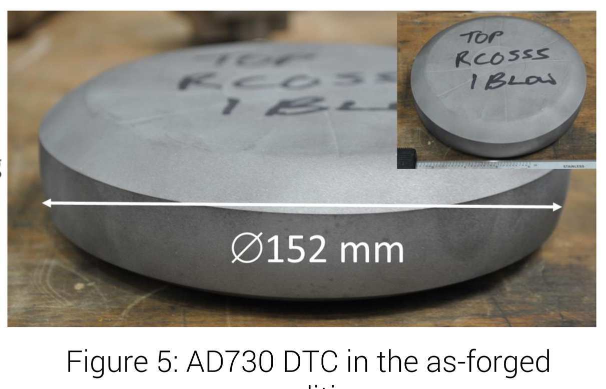


Figure 5: AD730 DTC in the as-forged condition

Microstructural analysis

Microstructural analysis of the hot forged DTCs were conducted by Scanning Electron Microscope (SEM) and Electron Back-Scatter Diffraction technique (EBSD) at 8 positions, covering a large range of strain [0.3 – 2 mm/mm], see Figure 6.

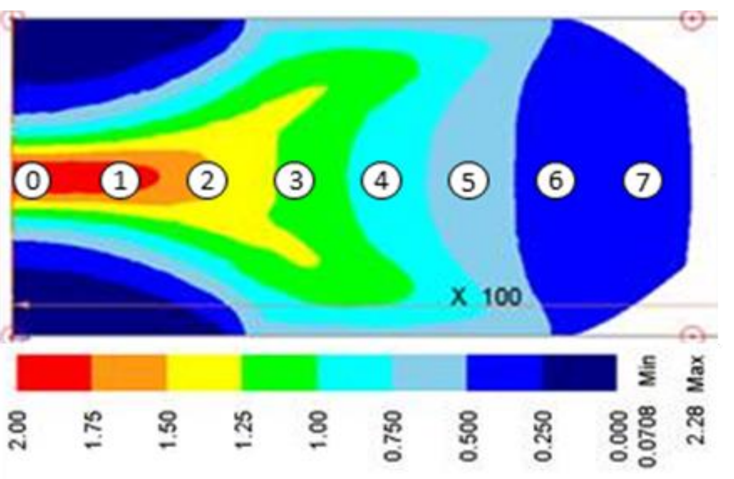


Figure 6. FEM simulation of effective strain distribution of hot forged AD730 DTCs

Results

Large differences in the size of γ' precipitates between recrystallized and unrecrystallized grains were found (Figure 7.a). In the fully recrystallized regions (Figure 7.b), characteristic primary and secondary γ' precipitates for this type of alloys can be observed. By contrast, the unrecrystallized grains present a much finer distribution of primary γ' precipitates (Figure 7.c).

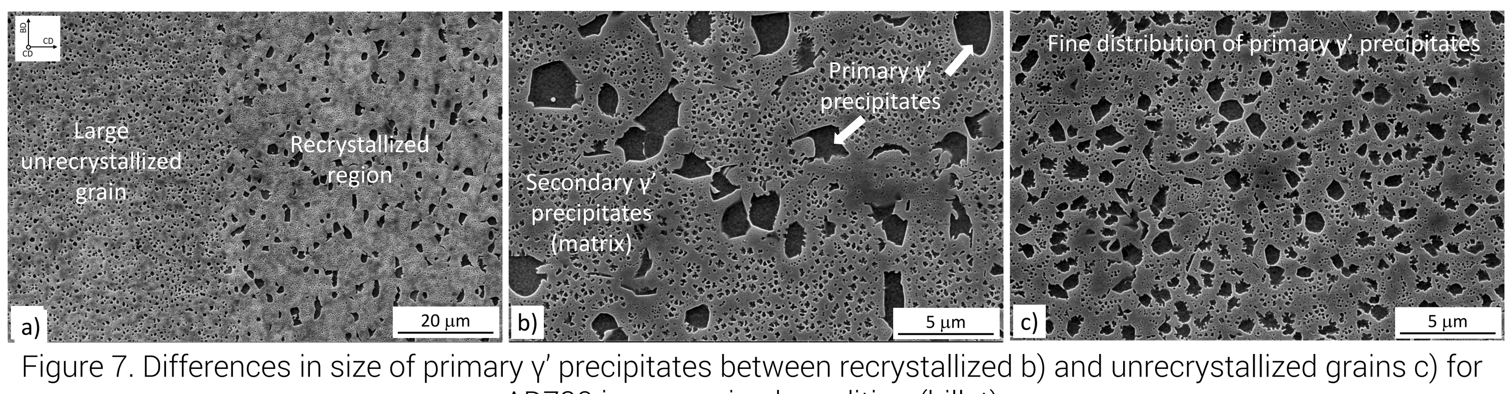


Figure 7. Differences in size of primary γ' precipitates between recrystallized b) and unrecrystallized grains c) for AD730 in as-received condition (billet)

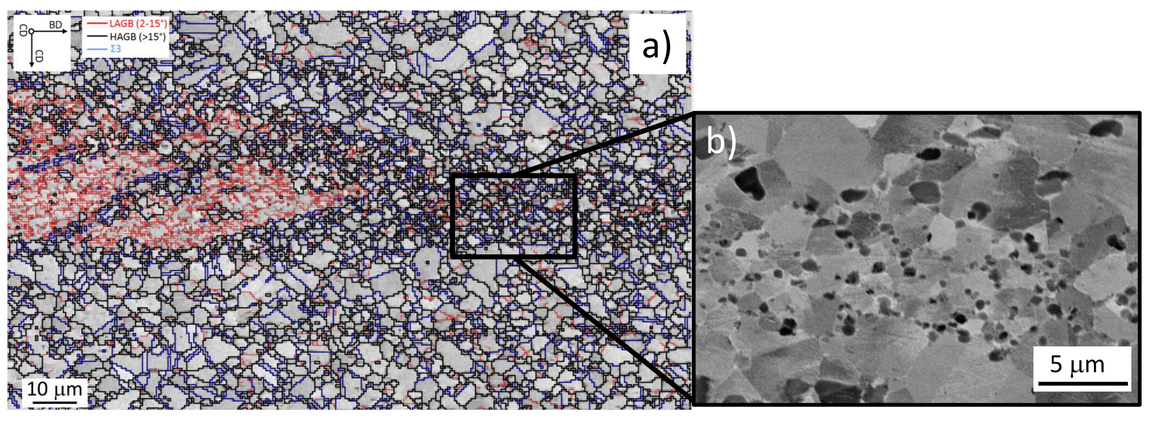


Figure 8. Position 1 (ε ≈ 1.8) – DTC forged in the cogging direction (CD)

Figure 8.a shows a tail of a large unrecrystallized grain, partially recrystallized, formed by a fine distribution of small equiaxed grains. Figure 8.b depicts a fine distribution of γ' precipitates, associated to prior unrecrystallized grains. These results confirm the strong pinning effect of intragranular γ' precipitates, playing a key role on grain size control, but also acting as main barriers to grain boundary migration for the occurrence of DRX.

For AD730, the strong pinning effect of the intragranular γ' precipitates inhibit the growth of DRX grains at the expense of the large unrecrystallized grains, resulting into strain accumulation during cogging operations, and promoting the occurrence of CDRX mechanism. Figure 9.a confirms the formation of intragranular MAGB and even HAGB. Microstructure fragmentation promotes the occurrence of deformation bands (Figure 9.b), providing nucleation sites for the nucleation and growth of new recrystallized grains in the interior of unrecrystallized grains.

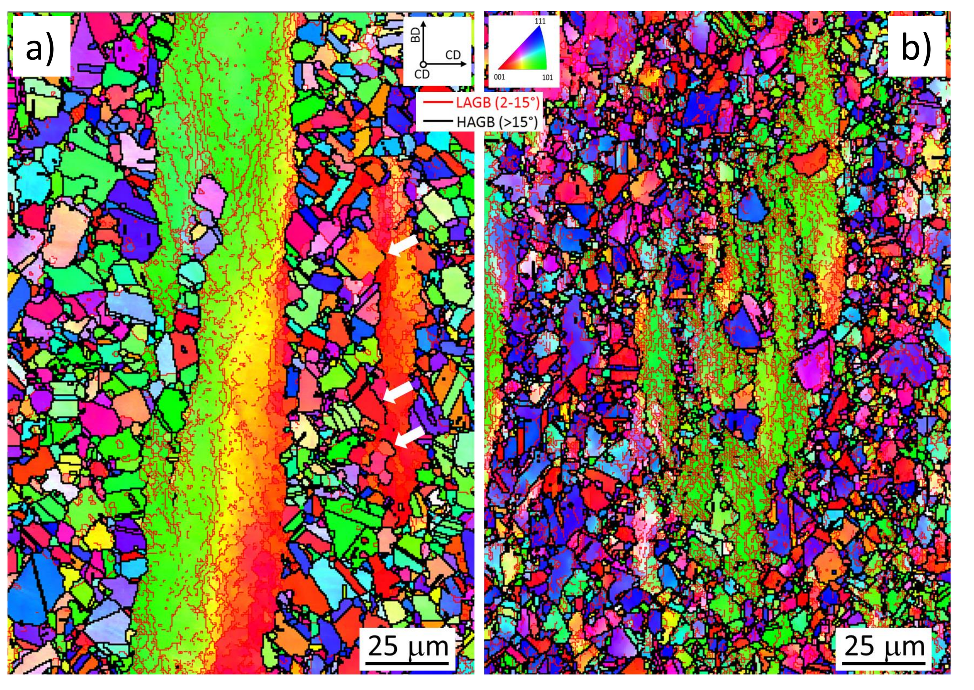


Figure 9. Formation of intragranular MAGB and even HAGB (white arrows) a), and intragranular RX grains b) in the interior of large unrecrystallized grains for AD730 material

Effect of forging direction and strain

Increasing fractions of strain-free structures can be observed as the level of deformation increases from ε ≈ 0.3 to ε ≈ 2 (Figure 10). However, strains as high as ε ≈ 2 do not present any significant effect. Similar results/tendencies were observed for both DTCs forged in the billet (BD) and cogging direction (CD).

Apparently, forging direction does not present any significant effect. Similar results/tendencies were observed for both DTCs forged in the billet (BD) and cogging direction (CD).

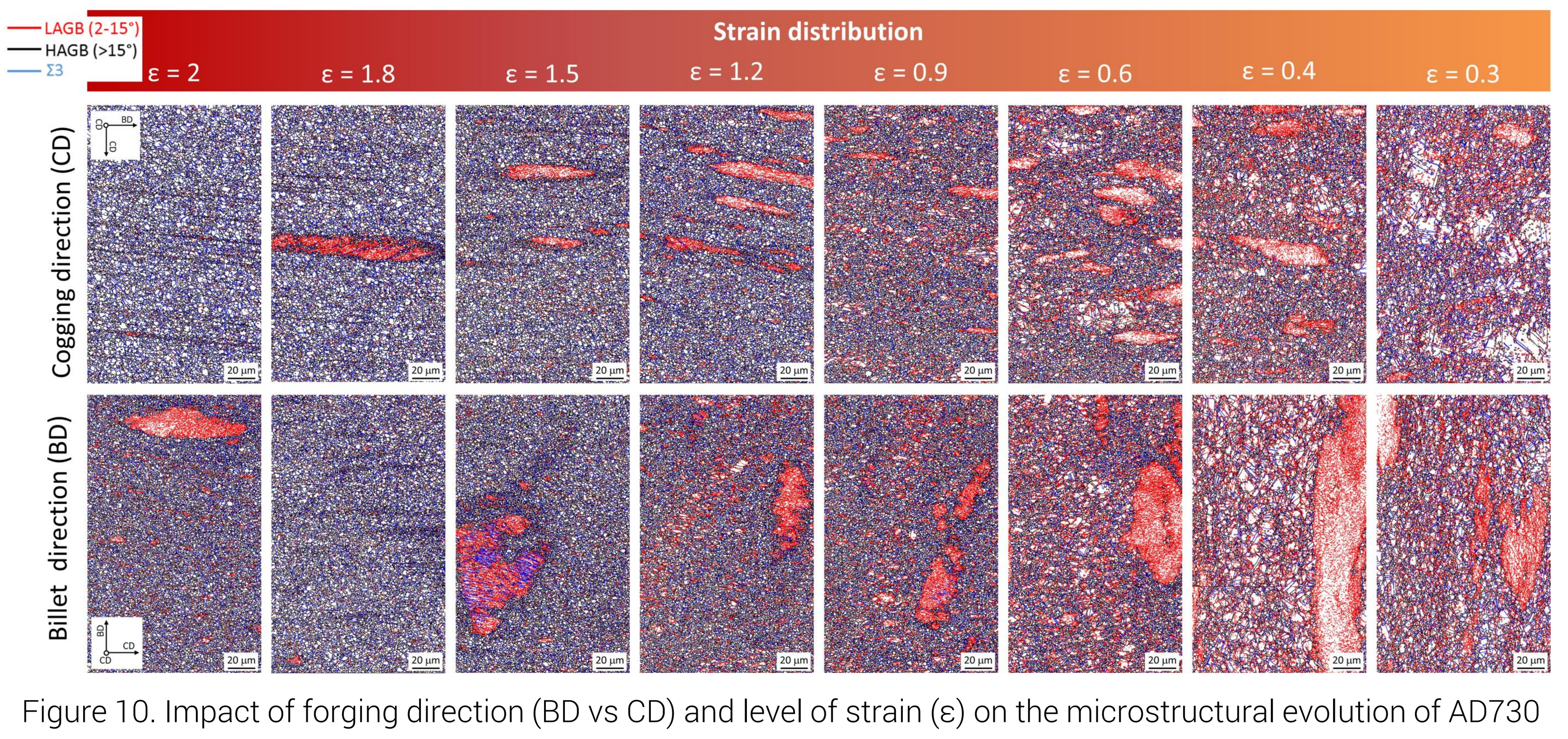


Figure 10. Impact of forging direction (BD vs CD) and level of strain (ε) on the microstructural evolution of AD730

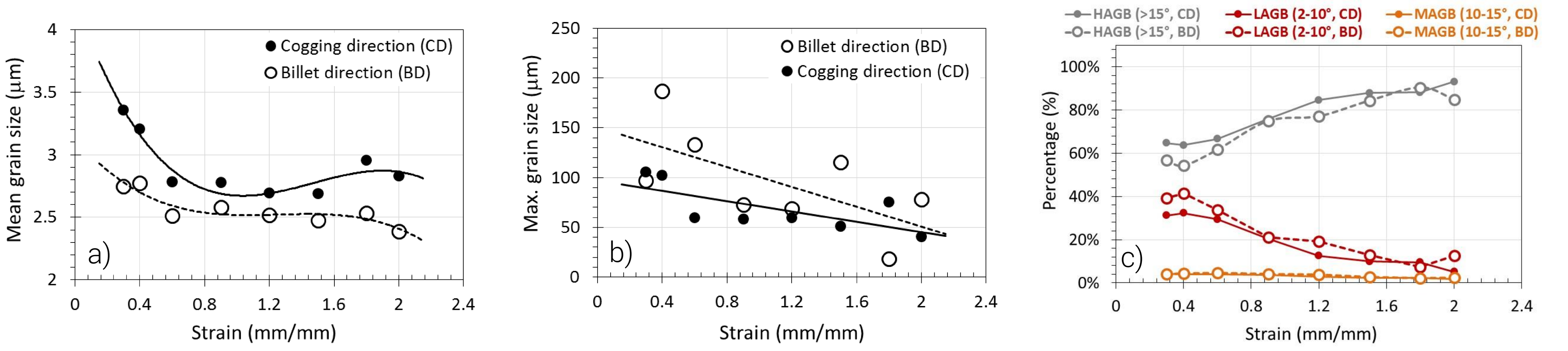


Figure 11. Evolution of mean grain size a), maximum grain size b), and low (LAGB), medium (MAGB) and high angle boundaries (HAGB) with strain.

The DTC forged in cogging direction (CD) presents a slightly but consistent larger mean grain size (Figure 11.a) but with a less scatter distribution of the maximum grain size (large unrecrystallized grain) than that forged in the billet direction (BD), see, Figure 11.b.

A linear increase of HAGB is accompanied by a reduction of LAGB as strain increases, denoting higher recrystallized fractions (Figure 11.c). Significant strain accumulation (high fraction of LAGB) is observed even in regions with relative high levels of deformation (ε ≤ 1.2).

Conclusions

AD730 billet material is characterized by a complex and heterogeneous microstructure with the presence of large unrecrystallized grains, strongly aligned in the billet direction. A very fine distribution of intragranular γ' precipitates within the large unrecrystallized grains were found. These precipitates play an important role on the DRX mechanisms which operate on AD730, promoting the occurrence of CDRX.

Strain presents the strongest effect on the microstructural evolution of AD730 alloy during hot forging at subsolvus temperatures (1070 °C). However, strains as high as ε = 2 do not warranty the attainment of a fully new-grained structure. The combination of relative small levels of strain at subsolvus temperatures is translated into large fractions of unrecrystallized structures (above 40%). Small differences associated to the forging direction were observed.